

Chemodynamics of the Milky Way and disc formation history: insight from the RAVE and Gaia-ESO surveys

Georges Kordopatis^{1*,**}, Rosemary F. G. Wyse², and James Binney³

¹ Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany

² Johns Hopkins University, Dept of Physics and Astronomy, 3400 N Charles Street, Baltimore, MD 21218, USA

³ Rudolf Peierls Centre for Theoretical Physics, Keble Road, Oxford OX1 3NP, United Kingdom

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Multi-object spectrographs have opened a new window on the analyses of the chemo-dynamical properties of old Milky Way stars. These analyses allow us to trace back the internal mechanisms and the external factors that have influenced the evolution of our Galaxy, and therefore understand fundamental aspects of galaxy evolution in general. Here, we present recent results from the *RA*dial *VE*locity *EX*periment (RAVE) and the *Gaia*-*ESO* survey. These surveys explore the Milky Way properties in different ways, in terms of sample size and selection, magnitude range, and spectral resolution. We focus here on (i) the first direct detection of evidence for radial migration within the thin disc, providing insight into the history of spiral structure of the Milky Way, and (ii) the chemo-dynamical characterisation of the metal-weak thick and thin discs, for which chemo-dynamical models still have difficulties in reproducing.

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1 Introduction

The disentanglement of the effects of past accretion events and of secular mechanisms in the evolution of the Milky Way is a complex task (e.g. Rix & Bovy, 2013; Sellwood, 2014). Large samples of stellar velocities and metallicities are very valuable in this endeavour, containing the signatures of past events (e.g. Eggen et al., 1962; Freeman & Bland-Hawthorn, 2002), with the caveat that the distributions functions (DF) of the different Galactic populations often overlap and change as a function of location within the Galaxy. In principle age is the parameter with the most power to discriminate among models of our Galaxy's history (e.g. Minchev et al., 2014). However, stellar ages have only recently started being derived with reasonable error bars, and for only a relatively small sample of stars, and potential biases in the derived ages may still exist (Miglio et al., 2013). The large-scale investigation of the chemo-dynamical properties of the stars constituting the different Galactic populations is therefore still the most robust way to understand how our Galaxy was formed and evolved. This is achieved by detecting and identifying the signatures predicted by models that incorporate different underlying formation mechanisms.

These signatures are encoded in the correlations among the spatial, chemical, and kinematic parameters of each stellar population. In order to detect these signatures, how-

ever, large statistical data sets are needed. For more than a decade, multi-object spectroscopic surveys have been gathering data with continually improving spectral resolution and/or for larger number of stars. Such surveys include the Geneva Copenhagen Survey (Nordström et al., 2004), the *RA*dial *VE*locity *EX*periment (RAVE, Steinmetz et al., 2006), the Sloan Extension for Galactic Understanding and Exploration (SEGUE, Yanny et al., 2009), the APO Galactic Evolution Experiment (APOGEE, Majewski et al., 2015), the *Gaia*-*ESO* Survey (GES, Gilmore et al., 2012) and the LAMOST experiment (Zhao et al., 2012). The ongoing *Gaia* mission (Perryman et al., 2001) will provide astrometric information for more than a billion stars with, in particular, measurements of the parallaxes and proper motions, in addition to photometric information and spectra for a significant fraction of the observed targets.

Here we review some recent results, obtained with RAVE data release 4 (DR4) (Kordopatis et al., 2013a) and GES DR2, concerning radial migration and the accretion history of the Galactic discs. These results are based on analyses of the properties of the tails of the metallicity distributions of the thin and thick disc, i.e. either the super metal-rich (Sect. 2) or the metal-poor ends (Sect. 3). Such analyses of course require large samples. Our perspectives and conclusions are presented in Sect. 4.

* On behalf of the RAVE and Gaia-ESO collaborations.

** Corresponding author: gkordopatis@aip.de

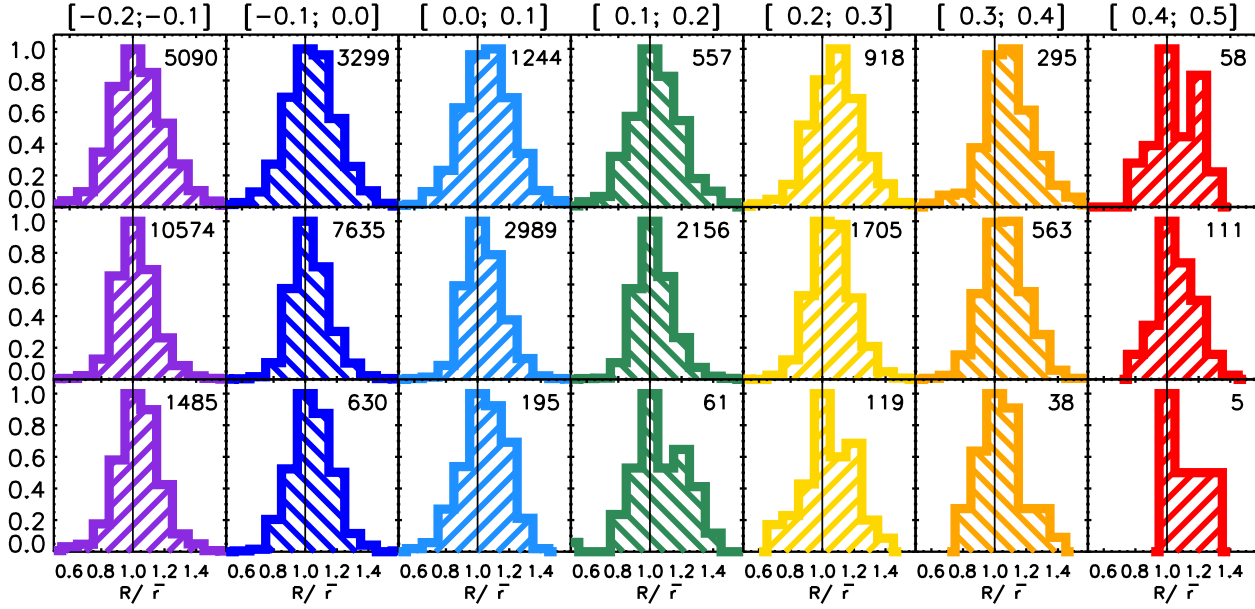


Fig. 1 Normalised histograms of the ratio between the observed radius and the mean orbital radius of the metal-rich RAVE stars for different metallicity bins (columns) and different Galactocentric radius rings (top: [6.5, 7.5] kpc, middle: [7.5, 8.5] kpc, bottom: [8.5, 9.5] kpc). The numbers in the upper right corners of each panel indicate the size of the sample used to compute that histogram.

2 Properties of the metal-rich end of the thin disc

Stars in the local thin disc that have metallicities of at least twice the Solar value (denoted as super metal-rich stars, SMR) carry important information concerning the secular evolution of the disc. Indeed, it is highly unlikely that these stars could have formed in the Solar neighbourhood, since the local inter-stellar medium (ISM) has only now reached Solar metallicities (Carlledge et al., 2006). These non-locally born stars could not have been accreted either, since a satellite galaxy containing stars of such high metallicity is expected to have been of high mass (Kirby et al., 2013) and therefore its accretion should have left significant phase-space imprints that so far have not been detected. The Super metal-rich stars have therefore been born within the disc and reached their present position either (i) through epicycle motion (therefore only passing through the Solar neighbourhood on a presumably outwards radial excursion around apocentre), or (ii) having radially migrated outwards, changing their mean orbital radius from the inner Galaxy to larger radii through interactions at the corotation resonance of transient spiral arms and/or the central bar of the Galaxy (e.g. Minchev & Famaey, 2010; Schönrich & Binney, 2009; Sellwood, 2014; Sellwood & Binney, 2002).

The RAVE survey operated for ten years and gathered data for more than 4×10^5 old FGK stars. Other than avoiding the lowest Galactic latitude fields, RAVE observed the Southern sky homogeneously. Kordopatis et al. (2015a) analysed the spatial and orbital properties of the most metal-

rich stars in RAVE’s 4th data release, and found that more than half of those with $[M/H]$ above 0.3 were in circular orbits, i.e. with a derived mean orbital (guiding centre) radius close to the radial coordinate at which the star is observed (see Fig. 1). This is strong evidence that these stars have reached the Solar neighbourhood through some mechanism that changed their orbital angular momentum but did not increase their orbital eccentricities, the most likely being radial migration induced by torques operating at the corotation resonance of a transient spiral perturbation (see for example, Sellwood & Binney, 2002).

The local SMR stars are estimated to have typical ages of ~ 6 Gyr, similar to the Sun. Assuming a fixed radial metallicity gradient equal to that of the ISM today (e.g. Genovali et al., 2014), the SMR stars should have been born in the inner regions of the Galaxy, $R \sim 2$ kpc. The results shown in Fig. 1 therefore highlight that interactions between stars and transient spiral patterns at their co-rotation resonances have occurred over a significant part of the history of the Milky Way, in order to bring a star born in the inner disc out to the Solar neighbourhood (its present position). Further, such metal-rich stars have been detected up to almost one kiloparsec above the Galactic plane. This puts further constraints on the history of the spiral structure in the Galaxy, since the gravitational field from the spirals should have been strong enough to influence stars at these heights. The gravitational field of a spiral of radial wave number k decreases exponentially with height above the plane, z , as $\exp(-kz)$ (Binney & Tremaine, 2008), implying the need for spiral perturbation of small wave number (long radial

wavelength) (cf. Solway et al., 2012). The requirement for stars to migrate over a significant fraction of the extent of the thin disc suggests these perturbations were also of high amplitude, meaning massive spiral arms (see Kordopatis et al., 2015a, for further details).

3 The metal-poor ends of the discs: is there evidence of past accretion events?

The lowest metallicities reached by the thick and thin discs are also directly linked to the history of the Milky Way. Indeed, the low metallicity tail of the thick disc provides constraints on the potential extragalactic origin of these stars, whereas the α -enhancement of the low-metallicity tail of the thin disc - and how it compares with the α -enhancement of the metal-rich tail of the thick disc - holds information on the possible gas accretion history of the Milky Way (e.g. Chiappini et al., 1997; Wyse, 1995).

3.1 The metal-weak thick disc

Selecting those RAVE stars located between 1 and 2 kpc from the plane and with metallicities below -1.5 dex, Kordopatis et al. (2013b) found a homogeneously spatially distributed rotating stellar population. The azimuthal velocity of this population was found to be correlated with metallicity, with the amplitude of the dependence being measured as $\partial V_\phi / \partial [\text{M}/\text{H}] \approx 50 \text{ km s}^{-1} \text{ dex}^{-1}$. This equals the correlation measured previously for stars in other surveys probing the canonical (more metal-rich) thick disc (Kordopatis et al., 2013c, 2011; Lee et al., 2011), suggesting that this low-metallicity population represents the metal-weak thick disc (MWTD). The large statistical sample of RAVE allowed the detection of the MWTD down to metallicities as low as -2 dex. Finally, despite not having accurate enough α -abundances to draw conclusions about their origin, the MWTD stars in Kordopatis et al. (2013b) did not show any particular distinction compared to the halo stars of the sample. The transition between the halo and the thick disc has recently been explicitly investigated by Hawkins et al. (2015) using APOGEE data, finding no chemical differences between the two populations. This confirms earlier results based on a smaller sample selected from RAVE, with follow-up high resolution spectroscopy (Ruchti et al., 2011).

These results highlight the smooth transition from the halo to the thick disc: the inner halo, thought to have been formed in situ (e.g. Carollo et al., 2007; Cooper et al., 2015) shows no chemical differences compared to the low-metallicity thick disc, possibly suggesting therefore that the latter was also formed in situ. This would be in agreement with the dynamical study of Ruchti et al. (2015), who investigated the distribution of orbital angular momenta of the stars in the Gaia-ESO catalogue and concluded that there was no evidence for accreted disc stars and therefore that

the Milky Way experienced a relatively quiescent merger history during the last 9 – 10 Gyr (cf. Wyse, 2001).

3.2 The metal-weak thin disc

Using the second internal data-release of the high-resolution survey Gaia-ESO¹, Kordopatis et al. (2015b) investigated, with a new approach, the metallicity ranges where an overlap of two populations (namely the thin and the thick disc) could be detected. This was achieved by determining the amplitude of trends in the azimuthal velocities as a function of the magnesium to iron ratio (as a tracer of α -abundances), for narrow metallicity bins and for stars located in the extended solar neighbourhood. The advantage of such an analysis is that it is very sensitive to the true tails of the metallicity distribution functions of the underlying populations without, however, assuming any functional shape for the MDF. Indeed, the value of the slope of the correlation between azimuthal velocity and α -enhancement, $\partial V_\phi / \partial [\alpha/\text{Fe}]$, is expected to be non-zero for metallicity bins where more than a single population exist, provided that a given stellar (mono-abundance) population has a lag in mean azimuthal velocity (compared to the local standard of rest) which is sufficiently different from that of the other population(s) in the same sample.

The results obtained for stars located in the extended solar neighbourhood ($7.5 < R < 8.5$ kpc and $|Z| < 1$ kpc) are shown in Fig. 2, where the correlations for the other velocity components are also plotted. From that figure, one can see that the trends for V_R and V_Z are always, within the errors, centred around zero. This indicates that the various stellar populations present in this (sub-)sample have the same mean V_R and V_Z (no expansion or contraction of the populations). In contrast, the V_ϕ panel shows clear trends, indicative of a mix of populations. In particular, it is found that the value of $\partial V_\phi / \partial [\alpha/\text{Fe}]$ is non-zero in the metallicity range $[-0.8, +0.2]$ dex. Furthermore, it is monotonically increasing for metallicities between $[\text{Fe}/\text{H}] = -0.6$ and $[\text{Fe}/\text{H}] \approx 0$. These facts have been interpreted as follows:

- The relative proportions of thin to thick disc stars changes as a function of metallicity, reflecting the difference in the mean metallicities of each population. However, there appears to be a constant fraction of thick to thin disc stars below $[\text{Fe}/\text{H}] \lesssim -0.5$, where the trend changes slope, and is consistently different than zero down to -0.8 dex.
- Both the thin and the thick disc have highly non-Gaussian shapes for their metallicity distribution functions. This result is in agreement with the existence of the super metal-rich tail of the thin disc (Sect. 2) and is compatible with the existence of the metal-weak thick disc (Sect. 3.1).
- The thin disc reaches metallicities as low as -0.8 dex.
- The thick disc reaches super-solar metallicities.

¹ The Gaia-ESO internal DR2 comprises roughly 10^4 stars

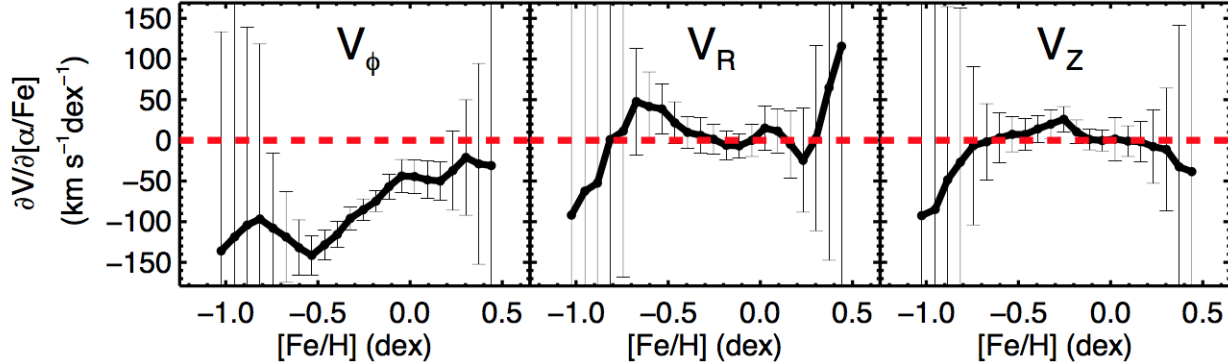


Fig. 2 Correlations between the $[\alpha/\text{Fe}]$ abundances and the three velocity components for the Solar vicinity stars ($7.5 < R < 8.5$ kpc and $|Z| < 1$ kpc) of the Gaia-ESO internal DR2. No trends are detected, within the errors, for V_R and V_Z . In contrast, a clear signal is measured for the azimuthal velocity, indicating that the thin disc extends down to at least $[\text{Fe}/\text{H}] \approx -0.8$ dex and the thick disc extends up to at least Solar metallicities.

As already noted at the beginning of Sect. 3, the α -enhancements of the metal-weak thin disc and of the metal-rich thick disc give valuable insight into the history of gas accretion into our Galaxy. For example, the analyses of Gilmore & Wyse (1986), Chiappini et al. (1997) or more recently Haywood et al. (2013), Snaith et al. (2014) and Bensby et al. (2014), suggest that the thick disc formed rapidly during an early, possibly turbulent, phase of the young Milky Way, and that at least part of the metal-poor thin disc formed subsequently, out of either newly accreted gas at the end of the star-forming epoch of the thick disc and/or from gas expelled from the thick disc.

According to these scenarios, the results derived from the Gaia-ESO data suggest two possibilities. The first is an accretion of a significant mass of metal-poor gas, to lower the ISM’s metallicity before the start of the thin-disc star formation, in order to reproduce the large metallicity overlap of the discs (over 1 dex). Alternatively, observations could also be explained with discs formed in an inside-out mode (likely combined with an violent event puffing up the thick disc), where in practice the metal-rich thick disc would have been formed in a different place than the metal-poor thin disc, without any need of decreasing the metallicity of the ISM at any radius.

4 Conclusions and Perspectives

The data already available allow us to gain insight into the formation processes of the Milky Way discs and the accretion history of our Galaxy. However, there are limitations, such as the relatively large uncertainties in distances (obtained through isochrone fitting) and proper motions (obtained from ground based surveys) leading to uncertainties in 3D space velocities of 40-80 km s⁻¹. In addition, individual stellar ages are very poorly known (the relative errors from isochrone fitting is 40 percent, if not more), and the stars for which we do have a reliable age estimate are within

the Hipparcos volume and thus are very nearby and similar in metallicity to the Sun.

In the coming years, the sample for which we will have astero-seismic ages and parallaxes and proper motion measurements from space observations will increase significantly. This will open new doors into our understanding of the formation of the Milky Way, such as identifying the relics of minor mergers and allowing ages to be determined for stars of different chemical compositions. This will in turn allow us to have a “live” picture of our Galaxy and understand the sequence of events that have taken place during the last 10 Gyr.

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